atmospheric river on part of the May ocean flights. The ocean color sensor obtained substantial data at cruise altitudes and in a spiral descent and ascent over a calm ocean surface.

The DCS successfully mapped Anacapa Island (http://uav.noaa.gov/altair/data/anacapa_mosaic_sm.jpg) and coastal segments of two larger Channel Islands. The EO/IR sensor images were distributed as streaming video over the Internet during the flight to a pre-selected audience of interested users. Aggregations of California sea lions and northern elephant seals and approved fishing and diving activities were observed at several Channel Island locations. Large commercial ships were spotted and successfully identified by vessel type from up to 16.1 kilometers away. During flight, the REVEAL system created aircraft status displays and three-dimensional maps of the Altair location.

Altair operated in both restricted and controlled areas of the National Air Space (NAS). Obtaining permission for Altair flights from the U.S. Federal Aviation Administration (FAA) was an important success of this demonstration project because of the location and complexity of proposed flight plans. The FAA and its regional centers on the U.S. west coast were cooperative regarding flight plan approval and in-flight coordination with Altair. In August 2005, the FAA granted Altair the first 'experimental certificate' for a UAS, which provides increased freedom for Altair to operate in the NAS (http://www.ga.com/). The 'experimental' marking on Altair can be seen in Figure 1. The certification is notable recognition of the quality and reliability of Altair operations and encouragement for expanded development and use of UAS technology in the NAS.

The Way Forward

With the Altair demonstration flights completed, work will focus on the interpretation and publication of the datasets. As a result of this project, NOAA has formally recognized the important role that Altair and related technology will play in NOAA's future by initiating a program to develop and direct UAS activities. A variety of UAS activities and collaborations are underway or planned. NOAA-planned Altair activities include a collaboration with NASA and the U.S. Forest Service on the Western States Fire Mission in 2006 and with NASA on the Aura Validation Experiment in 2007.

Additional ormation about the UAS program is available at http://uas.noaa.gov and http://www.uav.com/

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Reevaluating Hubbert's Prediction of U.S. Peak Oil

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In 1956, M. King Hubbert, chief consultant for the Shell Development Company's exploration and production research division, forecasted that U.S. oil production would peak in the early 1970s. He subsequently updated this prediction using newer data, but the predicted timing of peaking did not change significantly (see *Hubbert* [1982] for a review and references to earlier papers). In 1971, U.S. annual production of crude oil peaked at slightly more than three billion barrels (bbl).

Yet, Hubbert's model continues to be challenged by some. For instance, according to economist Michael Lynch, president of Strategic Energy and Economic Research, Inc., Winchester, Mass., it was only after Hubbert published his predictions "that the Hubbert curve came to be seen as explanatory in and of itself, that is, geology requires that production should follow such a curve" [*Lynch*, 2003].

This assertion is not supported by the geological literature. Long before Hubbert, geologists had pointed out that mining production follows a pattern of boom and bust:

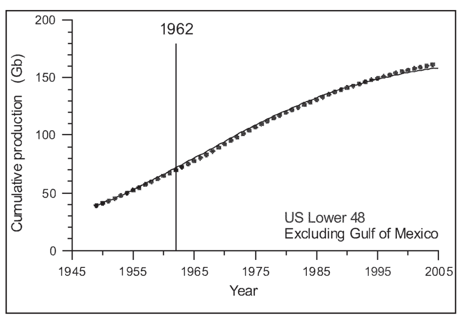

Fig. 1. Cumulative oil production in the lower 48 states (dotted curve), excluding production from the Gulf of Mexico, compared with the predicted trend (solid curve) obtained in 1962 by Hubbert based on production data to the left of the vertical line.

slow initial production preceding rapid growth as readily available resources are mined, followed by peak production and slow decline as remaining resources become more difficult to harvest. In 1889, geologist Edward Orton, after conducting a survey of the oil and gas resources in northwestern Ohio, warned that the local boom could not last long because "we are drawing upon a definite stock of this substance" [*Orton*, 1889].

It has been long recognized that geologic constraints are not the sole factor driving the production cycle. *Hewett* [1929], for example, discussed the importance of technology, economics, and political factors, which may influence the precise nature of the production curve. The recent surge in oil prices has resulted in increased interest in what used to be considered unprofitable oil resources, and fields previously considered uneconomical are now being exploited. Nevertheless, the primary driver of the cycle of mining production is the limited availability of the resource being mined. Without understanding these concepts, there would have been no reason for Hubbert to consider peak production and subsequent decline; the U.S. data available at the time (1956) applied to the period of rapid growth and by themselves showed no sign of an impending peak.

Much of the criticism revolves around Hubbert adopting the logistic model or bell-shaped curve. Hubbert recognized that production need not be symmetric but espoused the logistic model, which yields a parabolic curve for production rate, dQ/dt, as a function of cumulative production, Q, because this symmetry was dictated by the U.S. oil production data, not because of some a priori assumptions. Stressing this point, *Hubbert* [1982] wrote that, "it is to be emphasized that the curve of dQ/dt versus Q does not have to be a parabola, but that a parabola is the simplest mathematical form that this curve can assume. We may accordingly regard the parabolic form as a sort of idealization for all such actual data curves, just as the Gaussian error curve is an idealization of actual probability distributions."

By C. J. van der Veen

Other functional relations for resource production and depletion have been examined since, but none appears to offer substantial improvement over the logistic model when applied to U.S. production data. If critics wish to reject the logistic model, they should provide a credible alternative. Simply discarding Hubbert because one wishes to delay the timing of peak oil is unscientific.

Attempts to Discredit Hubbert

Lynch [2003] attempted to discredit Hubbert's model by stating that "oil production rarely follows a bell curve, as can be seen in *Campbell* [2003], where only 8 of 51 non-OPEC countries appear to do so." However, *Hubbert* [1982] discussed oil production in the state of Illinois to demonstrate that the smaller the region, the more irregular in shape the production curve is likely to be. Thus, for individual countries one would expect deviations from the bell curve; but for the aggregate, these irregularities tend to cancel out, and the production curve can be described by a bell curve, as the aggregate curve for the non-OPEC countries shows [see Figure 8.3, *Campbell*, 1997].

Concerning Hubbert forecasting the peak of U.S. oil production in the early 1970s, *Adelman and Lynch* [1997] acknowledged that Hubbert correctly predicted this peak, but they wondered whether this peak was the result of resource exhaustion or of cheaper imported oil that became freely available in the 1970s. Similarly, *Linden* [1998] stated that the U.S. peak "had nothing to do with any geological factors, but was merely a rational reaction to the realities of the global oil market." So, either Hubbert got very lucky or he must have been a visionary economist who could forecast the global oil market almost 20 years in advance. Either possibility seems unlikely.

How well do Hubbert's forecasts agree with production data? According to *Adelman and Lynch* [1997], not very well. They wrote, "[F]or the U.S., Hubbert in 1974 estimated URR [ultimate recoverable resources] at 170 billion bbl. Production to date has already been 170 billion bbl, proved reserves are 20 billion bbl, and annual accretions above two billion bbl. Output in 1996 was about twice Hubbert's forecast."

A similar argument is made by *Linden* [1998], who estimated that the potential ultimate crude oil recovery from the lower 48 states could range from 234 to 314 billion bbl, much higher than Hubbert's estimate. However, these authors are comparing apples to oranges.

Hubbert based his projections on production data for the U.S. lower 48 states. Until that time, offshore production in the Gulf of Mexico (GOM) was negligible. Thus, any comparison of Hubbert's projections with actual production data should be limited to the region included in the original analysis—onshore production in the lower 48 states—and exclude production in the GOM. This oil is shipped to terminals in the Gulf states and included in production numbers for these states. For a fairer assessment, GOM production data (available from the U.S. Minerals Management Service) should be subtracted from production data for the lower 48 (available from the U.S. Energy Information Agency). Comparing these data with Hubbert's prediction indicates a striking agreement.

Figure 1 shows production data for the lower 48 states, excluding the GOM, as well as the logistic curve based on ultimate recoverable resources of 170 billion bbl and an exponential time-decay constant of 0.00687 per year [*Hubbert*, 1982]. In 2004, cumulative production amounted to slightly more than 161 billion bbl. Extrapolating the production data into the future suggests the ultimate production will be about180 billion bbl, much closer to Hubbert's estimate than scenarios supported by Lynch, Linden, and others.

The World's Oil Outlook

It appears then, that 50 years ago Hubbert was correct concerning oil production in the lower 48 states. Whether or not the world's oil production will follow suit cannot be determined until well after the world's peak oil.

To predict when world oil production will peak, the world's ultimate recoverable reserves (WURR) need to be known. *Campbell* [1997] estimated the WURR to be 1800 billion bbl, of which 180 billion bbl has yet to be discovered. An assessment by the U.S. Geological Survey (USGS) suggested that the WURR may be more than twice that much, 3896 billion bbl, due to a combination of reserve growth in existing fields and discoveries in new fields [*USGS*, 2000].

Assuming a constant percentage growth rate of two percent with peak production occurring when the reserves-to-production ratio drops to 10, the U.S. Energy Information Agency (EIA) [*Wood et al.*, 2004] predicted that increasing the WURR from 2248 to 3896 billion bbl (the low and high estimates from *USGS* [2000]) delays peak production from 2026 to 2047—just 21 years. If a symmetric production curve is assumed, the peak is predicted to occur some 20 years earlier, but subsequent decline will be less precipitous than in the EIA scenarios [*Bartlett*, 2000]. For the USGS high scenario to become reality, the average rate of discovery of new oil fields has to be of the order of 22 billion bbl every year for the next 50 years, equivalent to finding oil deposits exceeding the size of the upper limits of estimated recoverable resources in the Arctic National Wildlife Refuge every year and a half for the next half century. In addition, reserves in existing fields have to grow accordingly, and improvements in drilling technology have to be made to maintain production from older and depleting fields at a sufficiently high level to satisfy the growing demand.

Orton's 1889 words became reality some 30 years later when production in northwestern Ohio came to an end. Numerous smaller communities have experienced their local 'peak oil' and gone from boom to bust, yet many people continue to hope or expect that some magical quick fix will solve the world's energy problems. Knowing that Hubbert's prediction for U.S. production of oil was on the mark, the question is whether to heed his warnings—lower our appetite for large amounts of low-cost energy, and develop alternative energy sources that may replace oil in the near future—or whether to be swayed by economists who claim that when the need arises, scientists and engineers will find innovative solutions to impending oil shortages.

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